Transionospheric pulse pairs originating in maritime, continental and coastal thunderstorms: Pulse energy ratios

Heidi E. Tierney

Los Alamos National Laboratory and

Department of Physics and Astronomy, University of Oklahoma, Norman

Abram R. Jacobson

Los Alamos National Laboratory

Robert Roussel-Dupré

Los Alamos National Laboratory

William H. Beasley

School of Meteorology, University of Oklahoma, Norman

Abstract
We examine the ratio of energy in the second pulse to energy in the first pulse for 2467 transionospheric pulse pairs (TIPPs). The TIPPs examined here have been attributed to thunderstorms occurring over maritime, continental, and coastal regions near the continental United States (CONUS). The mean values of the energy ratios are found to be 0.39±0.27 for continental TIPPs and 0.94±0.62 for maritime TIPPs. The energy ratio values for the coastal TIPPs exhibit a bimodal distribution representative of both the continental and maritime populations. Previous observational evidence has shown that the second pulse of a TIPP is the surface-reflected signal from the same source as the first pulse. We compare the observed pulse-energy ratios to the squared reflection coefficients of soil and seawater given by the Fresnel equations. The average values of the squared reflection coefficients for sources with vertical-plane and horizontal-plane polarization are consistent with the data.

1. Background and Introduction

Transionospheric pulse pairs (TIPPs) were discovered in 1993 with a wide-band (~28-166 MHz) transient electromagnetic pulse detector, called Blackbeard, onboard the ALEXIS satellite [*Holden et al.*, 1995]. TIPPs are distinguished from other naturally occurring radio emissions by several characteristics. *Massey and Holden* [1995] defined TIPPs as VHF signals consisting of exactly two broadband pulses, each with duration of a few microseconds. The time separation of the pulses is typically tens of microseconds. Each pulse exhibits a frequency dispersion that is indicative of a sub-ionospheric origin. These first investigators suspected that TIPPs were associated with thunderstorms because they were recorded when lightning activity was within the satellite's VHF horizon.

A second satellite, FORTE, was launched in August 1997 and its VHF receivers have also recorded many TIPP waveforms. FORTE carries two RF receivers, both of which are described in detail in *Jacobson et al.* [1999]. The receiver used in this study has two passbands; each is independently tunable in the range of 20-300 MHz with 22-MHz effective bandwidth. The TIPP data discussed in this paper were recorded using a 26-48 MHz frequency range. Both of the passbands have eight subbands of 1-MHz bandwidth that trigger independently. This design was implemented so that the receiver would trigger off of wideband signals and discriminate against carriers. The trigger threshold for each subband can be set at a fixed level, or at a selected dB level above the noise background. For a signal to be recorded it is typically required that 5 out of 8 of the subbands trigger within a several-microsecond coincidence window. Using this triggering scheme, a variety of broadband VHF signals from lightning, including TIPPs, have been recorded.

Though TIPPs originate below the ionosphere, similar pairs of intense VHF noise bursts have not been observed using ground-based instruments. It was first suggested that this was because of a satellite's unique vantage point. The first pulse of a TIPP could have its origin above the Earth's surface, and the second pulse could be a reflection of the radiation directed toward the surface from the same source as the first pulse [*Holden et al.*, 1995]. If this ground reflection hypothesis were true, the VHF noise bursts would have to include significant VHF radiation directed toward the Earth's surface. Investigators using ground-based VHF instruments have observed such radiation. As recorded from the ground, microsecond-duration, intense, noise-like bursts of VHF radiation accompany observations of a class of waveforms called narrow bipolar pulses attributed to lightning discharges [*Le Vine*, 1980; *Willett et al.*, 1989]. It has been suggested that the VHF bursts accompanying narrow bipolar pulses are the source of the first pulse of a TIPP [*Smith*, 1998]. Other authors have used time-correlation analysis to investigate the source of TIPPs. TIPPs were found to correlate in time with LF/VLF intracloud pulses, not unlike narrow bipolar pulses, observed by the National Lightning Detection Network (NLDN) [*Jacobson et al.*, 2000; *Zuelsdorf et al.*, 1998]. TIPPs have also been shown to correlate in time with waveforms classified as positive CG discharges by the NLDN [*Jacobson et al.*, 2000]. The discharges that produce narrow bipolar pulses and presumably TIPPs can occur in isolation [*Smith et al.*, 1998], or in conjunction with other kinds of lightning discharges [*Suszcynsky et al.*, 2000].

There is observational evidence in support of the hypothesis that the second pulse of a TIPP is a reflection of energy from the first pulse at the surface. First, it was experimentally shown that, in addition to seawater, desert sand could provide an adequate reflection surface for VHF pulses. To test the reflectivity of sand for the frequencies at which Blackbeard was operating an electromagnetic pulse (EMP) generator was flown on one balloon while a second balloon tethered above desert sand held a receiver [*Massey et al.*, 1998]. The sand was found to have a reflection coefficient as high as 0.94 ± 0.06 for horizontal-plane polarization and 0.78 ± 0.09 for vertical-plane polarization. The EMP generator was at an elevation angle of 23° with respect to the receiver for most of the experiment. This experiment has not been carried out for other surface materials.

In addition to the ground reflection hypothesis, a model in which two temporally linked VHF sources of atmospheric origin are responsible for the production of TIPPs was presented [*Roussel-Dupré and Gurevich*, 1996]. The first pulse is attributed to the onset of an electron avalanche in the thunderstorm. The second pulse originates tens of kilometers above the thunderstorm. The time separation of the two pulses in this theory is the time for the electromagnetic disturbance to travel between the low and high altitude regions of maximum VHF production. This time delay is a maximum for an observer situated on an axis that is perpendicular to beam propagation direction. An observer directly above the radio emission would observe the pulses almost simultaneously.

This relationship between the satellite observation angle and TIPP separation was later shown to be inconsistent with most of the TIPP data. As shown in [*Jacobson et al.*, 1999], for the majority of TIPPs, the time separation of the two pulses is a minimum for a low satellite observation angle and a maximum when the satellite is near the zenith with respect to the thunderstorm. This finding led TIPP investigators to believe unequivocally that the second pulse of a TIPP is the result of a surface reflection.

Despite this evidence, the surface reflection hypothesis has been questioned recently. One objection has been that the reflectivity of land may not be high enough to explain the large percentage of cases in which the second pulse is as intense or more intense than the first [*Rodger*, 1999]. It has been shown that a non-isotropic source such as a randomly oriented dipole radiator could account for some of these observations [*Massey and Holden*, 1995]. However, it still expected that the energy of the second pulse of a TIPP would depend on the reflecting surface. We address this topic using a data set of TIPPs that have been located by other means. In previous work, we explain a method by which one can determine the source thunderstorms for groups of satellite VHF data [*Tierney et al.*, 2001]. This is outlined in section 3.

We have examined the located VHF waveforms for the TIPP signature, and have identified 1038 TIPPs in maritime storms, 481 TIPPs in continental storms, and 948 TIPPs in coastal storms. To study the effect that a reflecting surface has on the second pulse of a TIPP, we examine the ratio of the energy in the second pulse to that in the first pulse for this data. We find a mean value of this pulse-energy ratio to be 0.39±0.27 for continental storms and 0.94±0.62 for maritime storms. These values are in overall agreement with known squared reflection coefficients for land and seawater.

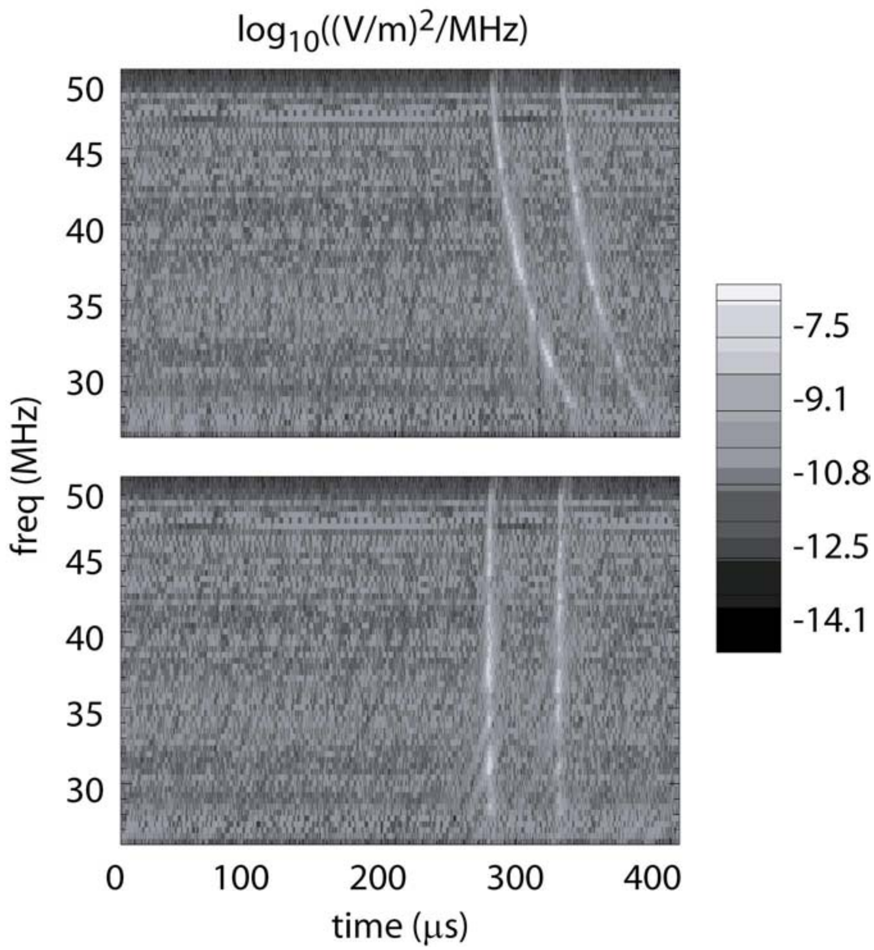

Figure 1: Example of a FORTE VHF periodogram of a TIPP. In the upper plot ionospheric dispersion is evident for both pulses of the TIPP. The lower plot has been corrected for dispersion.

2. Data Analysis

The data reported on here were obtained with FORTE's receiver tuned to a low frequency band (26-48 MHz). Impulsive VHF signals that have traveled through the ionosphere and have energy that spans much of the frequency range from 26-48 MHz exhibit frequency dispersion. The dispersion of each VHF signal can be corrected, and a value of total electron content (TEC), which is the path integral of the ionospheric electron density, can be obtained as explained by *Jacobson et al.*, [1999]. Each 400-μs recording of digitized electric-field data was corrected for dispersion and a value of TEC for the path through the ionosphere was determined. First, a fast Fourier transform (FFT) is repeatedly applied to 2.56-μs windows of each data record in steps of 0.16 μs. Thus, every 400-μs data record gets transformed into about 2500 spectrograms with frequency resolution of 0.39 MHz. Each spectrogram contains information on the average electric-field spectral density [$(V/m)^2$/MHz] as a function of frequency. When the spectrograms are displayed as a time series we refer to the result as a periodogram (Figure 1). These "de-chirped" periodograms are then summed over frequency to obtain the electric field squared. This quantity is divided by 377 ohms to obtain the Poynting flux incident at the satellite.

Plots of the power vs. time, such as Figure 2, were treated to obtain the time separations of the TIPP pulses and the time-integrated power in each pulse. This was achieved using graphical analysis. Time limits for which the power of each pulse is above the noise level, like the dashed lines in Figure 2, were estimated from logarithmic plots. To obtain the total pulse energy above the noise, the power of each pulse is integrated over time and the time integral of the average noise is subtracted from the total pulse energy. The energy in the second pulse is divided by the energy in the first pulse to obtain a value of pulse-energy ratio for each TIPP. In the results section we compare this quantity for our maritime, coastal, and continental TIPPs.

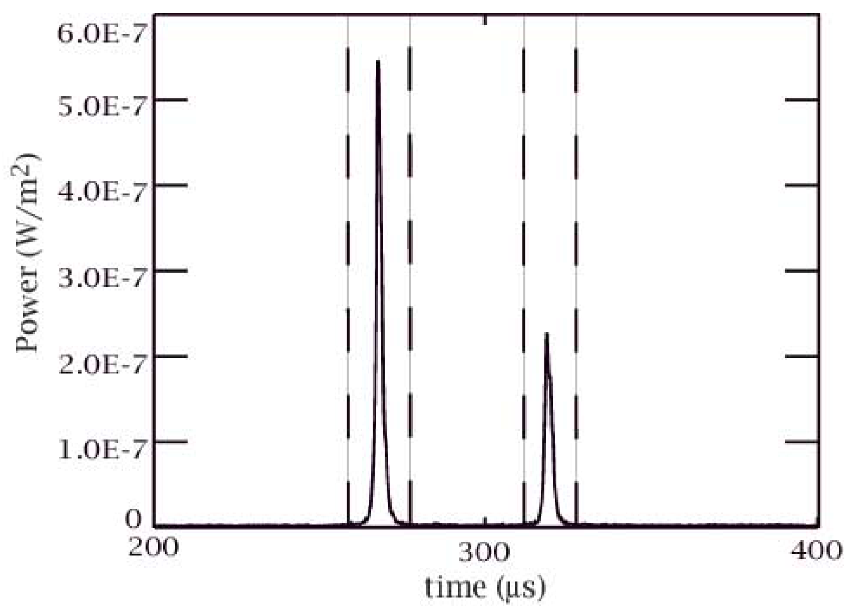

Figure 2: Plot of the frequency sum of the power for the TIPP in Figure 1. The dashed lines represent the limits within which the power of a TIPP pulse is time integrated.

3. Location Method

VHF signals originating from different locations on the Earth's surface often have values of TEC attributed to them that are different enough to distinguish one source from another. The TEC values from signals originating in different storms often form separate clusters in plots of TEC vs. time. In a previous work [*Tierney et al.*, 2001] we used this property of TEC to help assign median locations to some TEC clusters of satellite data. National Lightning Detection Network (NLDN) data were used to assign median locations and approximate sizes to the thunderstorms that produced the VHF emissions observed by FORTE. These authors required that a given cluster could be attributed to only one storm observed by the NLDN. To do this a subset of the VHF signals that had previously been assigned geolocations using time coincidence statistics [*Jacobson et al.*, 2000], and their measured values of TEC, were used to estimate the ionospheric conditions during each satellite observation run of interest. Using a simple model of the ionosphere, the paths from the NLDN locations to the satellite were assigned modeled values of TEC. A comparison of the modeled plots of TEC vs. time with the plots of satellite data helped eliminate cases in which more than one storm produced a single TEC cluster. In addition, only the storms that had lightning activity contained within $\pm 2.5°$ in latitude and longitude were considered. The NLDN data were used to determine the storm size, which gave a measure of the location uncertainty. For the months of April through September of 1998, the source thunderstorms for 65 groups of VHF satellite data records were determined. The locations and extreme coordinates of these groups are shown in Figure 3.

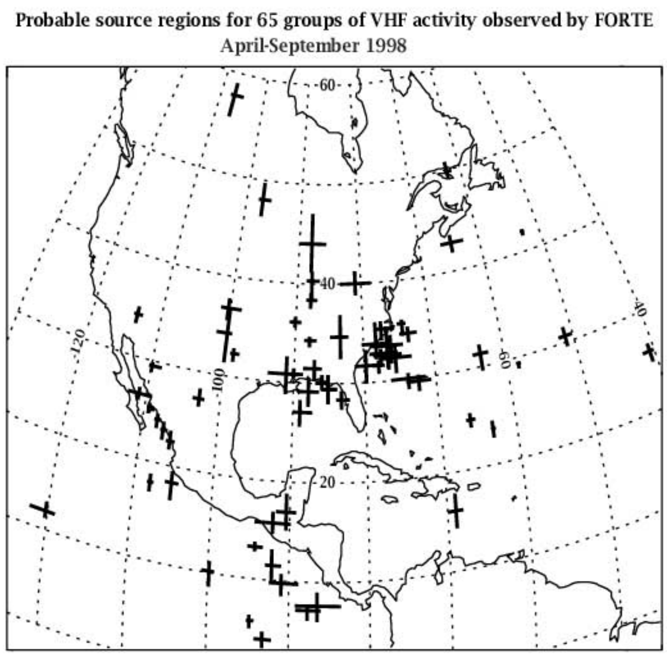

Figure 3: Approximate locations of VHF sources for the 65 groups of satellite data reported on here. Each cross center represents a median location assigned to one group of satellite data. The extreme values of latitude and longitude recorded by the NLDN during a satellite observation of a group define the limits of the cross axes. Adapted from *Tierney et al.* [2001].

4. Results

The 65 groups of located satellite data contain a total of 6131 VHF data records; 2467 of these data records have been identified as TIPPs. The data records have been assigned a median storm location only. We were able to locate events from 17 continental, 29 maritime, and 19 coastal storms. We define continental storms as those occurring entirely over land, as determined by the NLDN. Maritime storms are those in which all located events occurred over water. Coastal storms are those having at least one event located over land and one or more events located over water. Of the TIPPs that were assigned approximate locations in this study, 481 occurred over land, 1038 occurred over sea, and 948 occurred within coastal storms. Histograms of the energy ratios, or squared reflection coefficients, are plotted for these three populations in Figure 4. The percentage of TIPPs with an energy ratio falling at or below a given bin value is plotted in percent (right vertical axis). The TIPPs that originated in continental storms have a mean energy ratio of 0.39±0.27. This value is 0.94±0.62 for the maritime TIPPs. The energy ratio histogram for the coastal TIPPs exhibits a bimodal distribution. For the marine TIPPs a high standard deviation exists because there are a few cases in which the second pulse is about an order of magnitude more intense than the first pulse. For the continental TIPPs, there is a small but significant fraction of events with pulse energy ratios of about one.

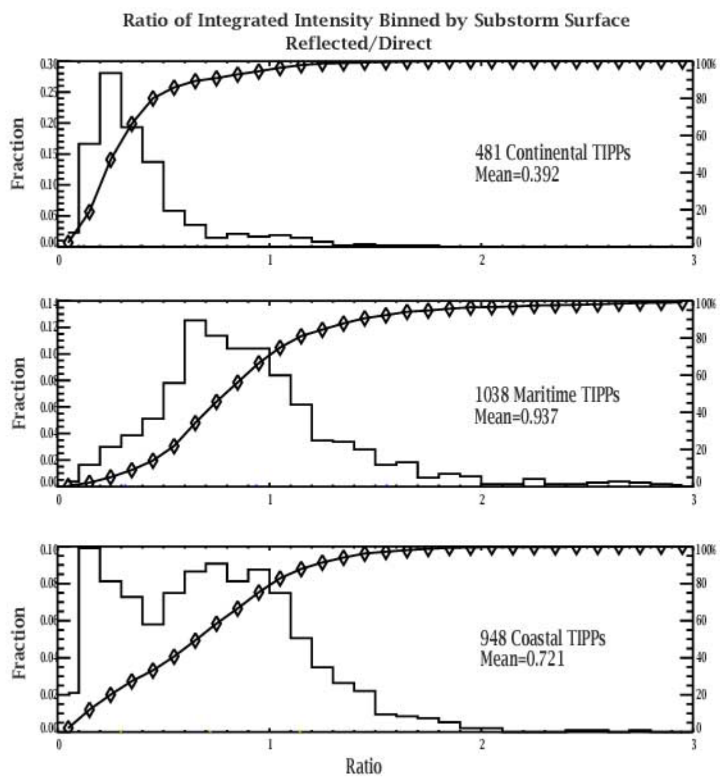

Figure 4: Histogram of the ratio of energy in the second pulse to energy in the first pulse for located TIPPs, and cumulative probability.

5. Discussion

We compare these results to those obtained using the the Fresnel equations [*Long*, 1983]. The Fresnel equations give the reflection coefficients for the horizontal-plane and vertical-plane polarization of an electromagnetic (EM) wave, R_H and R_V. In the following equations the horizontal component of an EM field vector is perpendicular to the propagation vector and lies in the plane of the reflecting surface. The vertical component is perpendicular to both the propagation vector and the horizontal component of the EM field vector.

$$R_H = \frac{\sin\alpha - (K - \cos^2\alpha)^{1/2}}{\sin\alpha + (K - \cos^2\alpha)^{1/2}} \quad (1)$$

$$R_V = \frac{K\sin\alpha - (K - \cos^2\alpha)^{1/2}}{K\sin\alpha + (K - \cos^2\alpha)^{1/2}} \quad (2)$$

In equations (1) and (2), K is the complex dielectric constant. The incident angle measured from the reflecting surface is α. The dielectric constant can be expressed in terms of its real and imaginary components.

$$K(\omega) = K'(\omega) - iK''(\omega) \quad (3)$$

Above, K' is the ratio of the dielectric permittivity, ε, of a medium to the permittivity of free space, ε_o. The imaginary component is inversely proportional to the frequency, ω, and proportional to the electrical conductivity, σ, of the reflecting surface.

$$K'' = \frac{\sigma}{\omega\varepsilon_o} \ . \quad (4)$$

The TIPPs analyzed here were recorded using a 26 to 48 MHz frequency range, and the corresponding wavelength range is about 11 to 8.25 m. The real and imaginary parts of the dielectric constant for oven-dry and water adsorbed soils in the frequency range of 30 MHz to 3 GHz have been measured by *Saarenketo* [1998]. For the dry and wet soil, we consider the measured, average values of the dielectric constant in the range of 30 to 50 MHz for use in equations (1) and (2). For seawater we use the results from a study of water salinity using 30-MHz radar by *Kachan and Pimenov* [1997]. The calculated reflection coefficients squared, for an algebraic average of the vertical-plane and horizontal-plane polarization, are shown in Figure 5. Note that for most of the range in elevation angle, the squared reflection-coefficients are in agreement with the mean values of the energy ratios of Figure 4. The angular dependence of the energy ratios can not be studied effectively with this data set. We only mention that the energy ratios examined here show no obvious correlation with satellite elevation angle.

One other feature of the histograms is worth noting. The pulse energy ratios for TIPPs occurring over water can be greater than one. In a study of Blackbeard TIPP data at two different frequency bands, 28-95 MHz and 117-166 MHz, [*Massey et al.*, 1998] found that one-third of the intensity ratio values were greater than one. This is similar to the current findings in which almost 25% of the values are greater than one. Most of these TIPPs are from the coastal and the maritime storms. There are at least two possible explanations for the cases in which the reflected pulse is more intense than the direct pulse. First, if the direct and reflected waves are partially polarized the polarization of the reflected waveform might result in a better match to the polarization of the antenna than the direct waveform. The direct and reflected propagation vectors will in general have different incident angles with respect to FORTE's antenna. The response of this antenna depends on the incident angle and is a maximum for waveforms travelling from satellite nadir. The polarization of the signals that are recorded as TIPP waveforms is currently under investigation by the FORTE team. Second, the radiation from the TIPP source may be non-isotropic and more power may be directed toward the ground than directly to the satellite. In this scenario, the energy reflected at the surface can be greater than that travelling directly to the satellite provided that the surface reflectivity is high as it can be for reflections from a water surface.

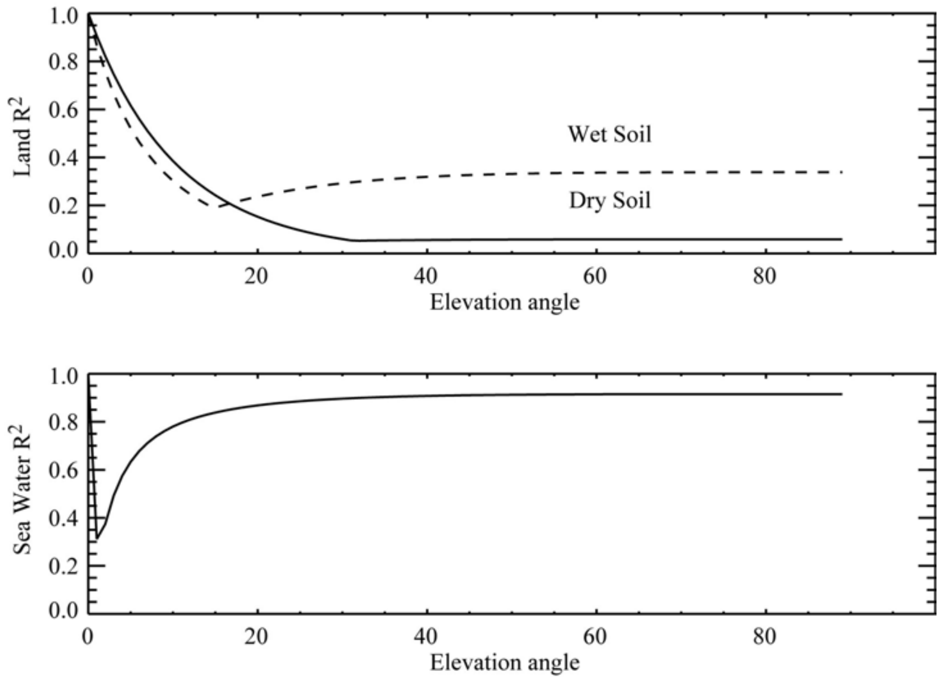

Figure 5: Average of vertical and horizontal reflection coefficients calculated from the Fresnel equations.

We have shown that the majority of TIPPs reported on here have pulse energy ratios that are consistent with a polarized source. The lightning physics that can explain these VHF pulses is still in question. Future work will include a detailed analysis of the polarization and energy of the observed waveforms. With this information it will be possible to set further observational limits to existing models.

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References

Holden, D.N., C.P. Munson, and J.C. Devenport, Satellite observations of transionospheric pulse pairs, *Geophys. Res. Lett.*, *22* (8), 889-892, 1995.

Jacobson, A.R., K.L. Cummins, M. Carter, P. Klingner, D. Roussel-Dupre, and S.O. Knox, FORTE radio-frequency observations of lightning strokes detected by the National Lightning Detection Network, *J. Geophys. Res.*, *105* (D12), 15,653, 2000.

Jacobson, A.R., S.O. Knox, R. Franz, and D.C. Enemark, FORTE observations of lightning radio-frequency signatures: Capabilities and basic results, *Radio Sci.*, *34* (2), 337-354, 1999.

Kachan, M.V., and S.F. Pimenov, Remote sensing of water salinity at decimeter wavelengths, *IEEE Trans. Geosci. Remote Sensing*, *35* (2), 1997.

Le Vine, D.M., Sources of the strongest rf radiation from lightning, *J. Geophys. Res.*, *85* (C7), 4091-4095, 1980.

Long, M.W., *Radar Reflectivity of Land and Sea*, Artech House, Inc., Dedham, MA, 1983.

Massey, R.S., and D.N. Holden, Phenomenology of transionospheric pulse pairs, *Radio Sci.*, *30* (5), 1645-1659, 1995.

Massey, R.S., D.N. Holden, and X.M. Shao, Phenomenology of trans-ionospheric pulse pairs: Further observations, *Radio Science*, *33* (6), 1755-1761, 1998.

Rodger, C.J., Red sprites, upward lightning, and VLF perturbations, *Reviews of Geophysics*, *37* (3), 317-336, 1999.

Roussel-Dupré, R., and A.V. Gurevich, On runaway breakdown and upward propagating discharges, *J. Geophys. Res.*, *101* (A2), 2297-2311, 1996.

Saarenketo, T., Electrical properties of water in clay and silty soils, *J. Applied Phys.*, *40*, 73-88, 1998.

Smith, D.A., Compact intracloud discharges, University of Colorado, Boulder, CO, 1998.

Smith, D.A., X.M. Shao, D.N. Holden, C.T. Rhodes, M. Brook, P.R. Krehbiel, M. Stanley, W. Rison, and R.J. Thomas, Distinct, isolated thunderstorm radio emissions, *J. Geophys. Res.*, *submitted*, 1998.

Suszcynsky, D.M., M.W. Kirkland, A.R. Jacobson, R.C. Franz, S.O. Knox, J.L.L. Guillen, and J.L. Green, FORTE observations of simultaneous VHF and optical emissions from lightning: Basic phenomenology, *J. Geophys. Res.*, *105* (D2), 2191-2201, 2000.

Tierney, H.E., A.R. Jacobson, W.H. Beasley, and P.E. Argo, Determination of source thunderstorms for VHF emissions observed by the FORTE satellite, *Radio Science*, *36* (1), 79-96, 2001.

Willett, J.C., J.C. Bailey, and E.P. Krider, A class of unusual lightning electric field waveforms with very strong high-frequency radiation, *J. Geophys. Res.*, *94* (D13), 16255-16267, 1989.

Zuelsdorf, R.S., C. Casler, R.J. Strangeway, C.T. Russell, and R.C. Franz, Ground detection of transionospheric pulse pairs by stations in the National Lightning Detection Network, *Geophys. Res. Lett.*, *25* (4), 481-484, 1998.